LOOKING GOOD IN WIRELESS SYSTEMS

Bountiful quartz, with the assistance of stabilization and tuning tricks, makes an ideal frequency reference for wireless systems.

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At one time, "wireless" was a Britishism for radio or RF. Now it's the in-vogue word for myriad portable and handheld devices, such as cellular phones, pagers, and global positioning systems (GPSs). All these systems need oscillator-based frequency references, either to establish a clock for digital circuitry or to generate a sinusoidal local-oscillator signal in downconversion (heterodyne) systems. Depending on the application, these oscillators need varying degrees of accuracy and stability. Nature has kindly provided an ideal frequency-reference medium in the form of quartz, whose excitation and resonance modes are predictable, repeatable, and eminently exploitable. You should understand some of the esoteric aspects of specifying crystal-based oscillators and know which "smaller, faster, cheaper" systems are available.

The various wireless-communications standards use a bewildering array of acronyms (**Table 1**). All these alphabet abusers need oscillators. Some systems, notably base stations, need very accurate and stable oscillators. In these oscillators, quartz crystals provide the basic frequency standard; oscillator-design techniques provide the necessary accuracy, tunability, and stability. Several basic types of crystal oscillators are available, and each type suits certain applications (**Table 2**).

Before delving into the characteristics of the many types of crystal oscillators, it might be useful to review a few fundamentals of the frequency-setting crystals. The entry "Quartz crystal" in **Table 2** is actually misleading: A quartz crystal in itself is not an oscillator; it needs active excitation and a passive reactive network to generate a frequency. If you feel adventurous, you can use a crystal to design your own oscillator, as in **Reference 1**, which gives design techniques for ASIC-based crystal oscillators. If you have stringent accuracy or stability needs, however, you'd probably do well to leave it to the experts—the oscillator manufacturers.

A crystal's frequency (fundamental or nth overtone), stability, tunability, and temperature characteristic depend on the way the crystal is cut. Temperature characteristics differ among crystals using FC, IT, SC, and doubly rotated AT cuts (**Figure 1**, derived from **Reference 2**). The inflection temperature, T_i, (which is also the zero-crossing point, at which the second derivative equals zero) varies significantly from cut to cut. You can see some of the trade-offs involved in selecting a crystal type. Curve 0 for the AT-cut type, for example, yields the flattest temperature coefficient at 25°C, but it also exhibits the greatest frequency variations at both low and high temperatures.

Though crystals are among the most fundamental of circuit building blocks, you could spend a lifetime studying the various cuts and growing techniques, with their concomitant effects on temperature characteristics, aging, phase noise, drive level, retracing (hysteresis), and vibration susceptibility. **Reference 3**, for example, explores the parametric influence of cut angles and other variables for doubly rotated SC-cut crystals. Note that quartz is not the only material that can generate frequencies. For applications that don't require the utmost in stability, you can also use ceramic or SAW resonators (see **box** "Quartz: not always a crystal-clear choice").

XO types and variations

The most simple type of frequency reference is the uncompensated and nonadjustable crystal oscillator. The principal application of these devices is as clock oscillators in wireless and other applications. The frequency variation with temperature of these oscillators follows the sinusoidal-looking crystal curves of **Figure 1**. Like most other components, crystal oscillators are becoming increasingly available in surface-mount, tape-and-reel format. The parameters you need to specify when ordering these devices are frequency, package type, supply voltage, accuracy and temperature stability, output waveform (square or sinusoidal), and output-drive format (TTL, CMOS, or ECL, for example). Another parameter of interest in some critical applications is jitter, usually specified in picoseconds rms or picoseconds absolute (peak-to-peak).

@a glance

- Our great-grandparents used quartz as a frequency reference; most likely our great-grandchildren will, too.
- The cut type and overtone mode influence the frequency, stability, and pullability of a crystal.
- Take your pick: VCTCXO=TCVCXO, and VCOCXO=OCVCXO.
- A VCO in a PLL system offers a much wider tuning range than does a VCXO.
- SAW and ceramic resonators are low-cost alternatives to quartz oscillators.

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Though the temperature-variation curves in **Figure 1** may look forbidding, keep in mind that the parts-per-million scale on the vertical axis can be small. Uncompensated crystal oscillators are available with ±25-ppm total accuracy. Total accuracy includes initial accuracy and variations with temperature, supply voltage, and load. Ecliptek's ECH1100/1300 Series of 70- to 155.52-MHz oscillators offers this ±25-ppm option, as well as ±50- and ±100-ppm choices. Designed for SONET and other applications, the high-speed CMOS (HCMOS)/TTL devices operate from 5 or 3.3V supplies. The devices' maximum aging spec is 5 ppm/year, and maximum absolute jitter is ±200 psec.

Pletronics offers ±15-, ±30-, or ±50-ppm initial accuracy at 25°C for its 32.768-kHz S3275L oscillator, which the company designed for cellular and PCMCIA applications. The spec sheet gives a formula for temperature variations, equating to approximately 70 ppm maximum at 70°C. The $1.85 (100,000) S3275L operates from a 5, 3.3, or 2.7V supply. Its output duty-cycle limits are 45/55 to 55/45%, and it comes in a 2-mm-high plastic surface-mount package. Three orders of magnitude higher in frequency, the 34.56-MHz SQ3344EV targets GSM (Global System for Mobile communications) systems. Temperature stability for the CMOS-compatible oscillator is ±25 ppm maximum over –40 to +85°C. It costs $2 (10,000) and comes in a 12.7-mm- sq, 6-mm-high metal can.

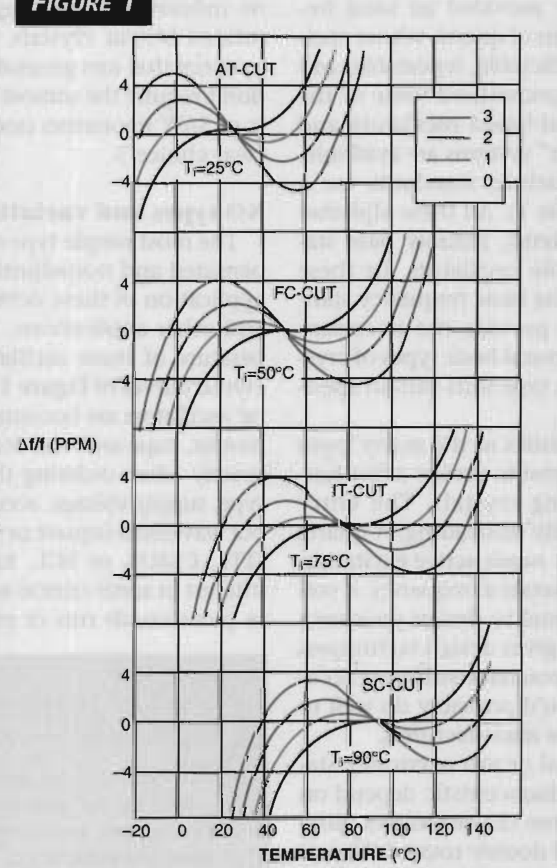
Designed for use as a master clock in wireless and other applications, the 1- to 67-MHz P3290 oscillator from MF Electronics specs a minuscule 10-psec rms jitter. The CMOS/TTL-compatible, surface-mount device is available in versions offering ±50- or ±100-ppm stability over 0 to 70°C. It specs 40/60% or better duty-cycle symmetry. Prices start at $1.95 (1000). Temperature stability is the hallmark of oscillators from Champion and AVX. Champion's 1- to 40-MHz MSO2 specs ±20-ppm maximum variation over 0 to 70°C; ±32 ppm from –40 to +85°C. The CMOS/TTL-compatible, surface-mount device costs $8.87 (1000). The 8- to 68-MHz K50 from AVX specs 50-ppm stability over temperature. The HCMOS-compatible, surface-mount oscillator measures only 1.6 mm high. It costs $2 to $5, depending on quantity and options.

Surface-mount oscillators from Fox Electronics target wireless applications. The F3345 and F3355 series, for example, covers the 1.8- to 80-MHz and 1.8- to 50-MHz bands, respectively. Frequency stability is ±100 ppm maximum under all temperature, supply, and load variations. The $2.26 (6000) devices come in hermetically sealed ceramic packages that boast shock resistance to 3000g. An ECL-compatible oscillator from Standard Crystal Corp offers frequencies of 20 to 120 MHz, with ±100-ppm stability over 0 to 70°C. The metal-encased device costs $14.80 (units). Epson America Inc offers turnaround of days instead of weeks for its $1.45 (10,000) SG-8002 oscillators. The devices cover the frequency bands 1 to 125 MHz (5V supply) or 1 to 90 MHz (3.3V supply) and offer ±100-ppm stability over –40 to +85°C.

The crystal oscillators discussed so far use fixed components in the network connected to the crystal. So, except for minor passive-component variations, the oscillator's temperature stability is equivalent to that of the crystal. A temperature-compensated crystal oscillator (TCXO) uses a thermistor-resistor network and a varactor diode (a voltage-dependent capacitor) to compensate for the crystal variations (**Figure 2**). The compensation technique is tricky. The manufacturer must tailor each compensation network to each crystal. Further, because of the complexity of the crystal's temperature curve, it's usually necessary to use multiple thermistor networks with several interdependent variable components. The tailoring job usually involves the computer-aided technique of simultaneous equations.

Despite the trickiness of the custom-tweaking procedures, oscillator makers offer units with remarkable stability figures. Among the tightest stabilities is the ±0.25 to ±1 ppm over various temperature ranges, including –55 to +85°C, for the $60 (OEM) XO3080 from Piezo Technology Inc. The low-profile, 0.24-in.-high oscillator is available in surface-mount or through-hole format and with optional sinusoidal or logic outputs. TCXOs from Fox Electronics and Fordahl spec ±1-ppm stability over their respective temperature ranges. Fox's $11.95 (1000) Model 790 covers 9.6 to 20 MHz. The company offers two versions that accommodate ±2-ppm frequency fine-tuning: The 790B accepts a digital stream, and the 790C uses an analog voltage. Fordahl's $122.05 (10) 5- to 30-MHz DFA

FIGURE 1



The turnover point (negative peak) of a quartz crystal is a function of the type of cut. An oven-controlled crystal oscillator uses a crystal with a high turnover temperature, because the first derivative of frequency with temperature is zero at that point.

S7 operates from 5 or 3.3V supplies and offers HCMOS-compatible or clipped-sine-wave outputs.

For slightly less demanding applications, some recent oscillators from Fox, AVX, and Bliley Electric Co offer better than ±3-ppm stability over temperature. Fox's 10- to 22-MHz Model 801 displays ±2.5 ppm stability over –30 to +75°C. The 2-mm-high surface-mount devices are also available in voltage-controlled TCXO (VCTCXO) versions that permit adjustments of ±5 or ±8 ppm. The 801 devices cost $7.90 (1000). AVX's KT Series specs ±2-ppm stability over –30 to +80°C and offers frequencies from 12.8 to 19.68 MHz. The 2.3-mm-high surface-mount devices cost $10 (2000). Bliley's 1- to 40-MHz T79C specs ±1.5-ppm stability over –40 to +85°C; units with even tighter stability are available on special order. The metal-encased T79C is compatible with HCMOS and TTL loads. A 30-MHz T79C costs $55 (100).

Oven-baked goodness

As impressive as the temperature stability of the TCXOs is, it pales in comparison with the stability of oven-controlled crystal oscillators (OCXOs). An OCXO keeps the crystal temperature constant by using a closed-loop thermostat system and a heating element inside the oscillator's case. The heating element keeps the crystal's temperature at its lower turnover point, the bottom valley of the almost sinusoidal temperature curve. This point has the smallest slope (zero) of the curve, so small changes in temperature cause almost no shifts in frequency. The proportionally controlled oven can improve the crystal's temperature stability by more than 5000 times.

The double-oven Model 4895 from Oak Frequency Controls covers the frequency range of 4.096 to 15 MHz. Its temperature stability is 2×10^{-10} (0.0002 ppm) over 0 to 75°C; double that figure for –20 to +75°C. Models with even greater stability are available on special order. The 4895's aging spec is $\pm3\times10^{-8}$ (0.03 ppm) per year, and it comes in a 50.8×50.8×38.3-mm package. The most stable OCXOs come in relatively big packages; smaller packages entail compromises in performance. For example, Oak's 10- to 25-MHz surface-mount OCXO has a stability spec of $\pm5\times10^{-8}$ (0.05 ppm) over 0 to 70°C. Note that all OCXO data sheets specify warmup time. The 4895, for example, requires 5 minutes to warm up to within ±0.01 ppm of final frequency.

The model 275 OCXO from Piezo Crystal Co uses SC-cut crystals to obtain better than 5×10^{-9} (0.005 ppm) total deviation over 0 to 75°C, with maximum aging of 0.05 ppm per year. Designed for demanding systems such as GPS, the 275 costs $170 (500). The OCX96 from CTS Frequency Controls offers a choice of SC- or AT-cut crystals, with respective stabilities of ±0.02 and ±0.1 ppm. The device offers both square and sinusoidal outputs. A frequency-control input allows

TABLE 1—WIRELESS-COMMUNICATIONS DESIGNATIONS

Acronym	Meaning
AMPS	Advanced mobile-phone service
BSS	Base-station system
CDMA	Code-division multiple access
CDPD	Cellular digital-packet data
CT-1	Cordless telephone, first generation (current cordless)
CT-2	Cordless telephone, second generation (outbound public and inbound/outbound home service
DECT	Digital European cordless telephone
DSSS	Digital sequence spread spectrum
EAMPS	Expanded advanced mobile-phone service
E-TDMA	Enhanced time-division multiple access
FDMA	Frequency-division multiple access
FHSS	Frequency-hopping spread spectrum
GPS	Global positioning system
GSM	Global System for Mobile communications—the pan-European digital-cellular standard
ISM	Industrial, scientific, and medical applications (frequency allocation 0.915, 2.4, 5.8 GHz)
N-AMPS	Narrowband advanced mobile-phone service
PCN	Personal communications network
PCS	Personal communications system/service
SMR	Specialized mobile radio
TDMA	Time-division multiple access
WAN	Wide-area network
WLAN	Wireless local-area network
WLL	Wireless local loop

Note: Table courtesy Murata Electronics.

TABLE 2—CRYSTAL-OSCILLATOR TYPES

Type	Applications	Stability (ppm) (0 to 70°C)	Packaging
Quartz crystal	Roll-your-own oscillators	20 to 100	Typically in sealed metal can
Uncompensated crystal oscillator	Digital-system and µP clocks	20 to 1000	Typically in DIP; volume less than 0.1 in.³; surface-mount devices available
Temperature-compensated crystal oscillator (TCXO)	Telecomm, test equipment, satellite communications	0.1 to 5	Various through-hole and custom packages; volume less than 0.5 in.³; surface-mount devices available
Voltage-controlled crystal oscillator (VCXO)	Telecomm, cellular, GPS, as a component in TCXOs and PLLs	20 to 100	Various through-hole and custom packages;volume less than 0.5 in.³; surface-mount devices available
Oven-controlled crystal oscillator (OCXO)	Frequency counters, spectrum and network analyzers, navigation and defense, base stations	0.0001 to 5	Various through-hole and custom packages; volume less than 0.1 in.³ with reduced stability; to 100 in.³ for high stability
Digitally/µP-compensated crystal oscillator (DCXO/MCXO)	Video, military, telecomm, high-end base stations	±0.02 to ±1	Various through-hole and custom packages

Note: Table courtesy NEL Frequency Controls.

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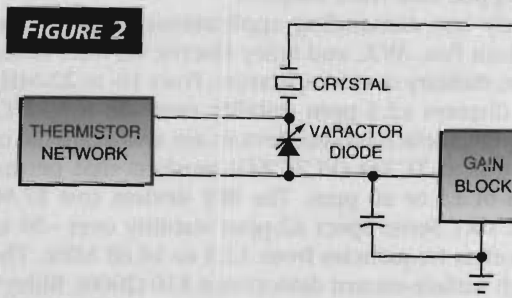
you to fine-tune the frequency in a range of ±3 ppm, using a 0 to 5V control voltage. Bliley's 2.5- to 20-MHz NV45A also offers the choice of AT- or SC-cut crystals, both with stability of $\pm 6 \times 10^{-8}$ (0.06 ppm) over –30 to +70°C. The AT-cut version offers ±2-ppm frequency tunability; the SC-cut version, ±0.5 ppm. The NV45A comes in a 26.2×26.2×13.5-mm case, which is small by OCXO standards. The SC-cut NV45A costs $150 (100).

Also small as OCXOs go, the CO-750 and CO-760 from Vectron International come in 38×38×12.7-mm and 25.4×25.4×12.7-mm packages, respectively. The 5- to 25-MHz oscillators provide stability options of ±0.1 to ±0.01 ppm over 0 to 50°C, with aging rates from 2 to 0.02 ppm per year. The 750 and 760 cost $139 and $153 (100), respectively. A final example of recently announced OCXOs is Fordahl's $53.31 (10) DFO 236-M, a 4- to 60-MHz oscillator with stability of ±0.05 ppm over –20 to +70°C and aging of 0.1 ppm per year. Available outputs include two HCMOS/TTL outputs and a sinusoidal output. Options include an external voltage control for pulling the frequency by 1 ppm.

You'll recall that some of the crystal oscillators have jitter specs. The OCXOs' spec sheets introduce the sinusoidal equivalent of jitter, called "phase noise." Many manufacturers' catalogs give good, detailed explanations of oscillator-applicable terms, such as phase noise (see **References 4** and

FIGURE 2



A complicated, multiresistor/multithermistor network compensates for the nonlinear frequency drift of a quartz crystal. The interactive adjustment requires a computer to solve simultaneous equations.

5). In succinct terms, phase noise is the ratio of signal power to noise power, measured in a 1-Hz bandwidth at a given offset from the desired signal. A typical crystal oscillator has three phase-noise regions (**Figure 3**, derived from **Reference** 5). The "flicker" noise (region A) is primarily a function of the quality of the crystal. The "1/f" noise (region B) stems from semiconductor activity. The "white," or broadband, noise (region C) represents the noise floor.

QUARTZ: NOT ALWAYS A CRYSTAL-CLEAR CHOICE

Aside from atomic resonance, quartz offers the most stable and predictable frequency-reference material. However, in applications that don't require quartz stability, several other methods and media are available for generating frequencies. Perhaps the first that springs to mind is an LC circuit connected to a gain block in a Colpitts or Hartley configuration, for example. Disadvantages of this method include considerable physical bulk and significant temperature drift.

Another popular frequency generator for wireless applications is the SAW resonator or oscillator. This method involves the propagation of waves across the surface of a resonator, as opposed to the shear-mode vibrations in the body of a crystal. Advantages of the SAW approach include small size and low cost. For example, the KAR-CK family of 315- to 450-MHz resonators from AVX comes in TO-39 metal cans and costs $1.50 (1000). The primary application is in such products as automotive keyless-entry systems, garage-door openers, security systems, and remote vehicle-identification equipment.

Vectron International and Murata also offer a range of SAW resonators and oscillators. A typical SAW oscillator from Vectron, for example, generates 433.92 MHz with ±250-kHz tolerance. SAW stability of ±1.50 ppm over –20 to +70°C and phase noise of –70 dBc

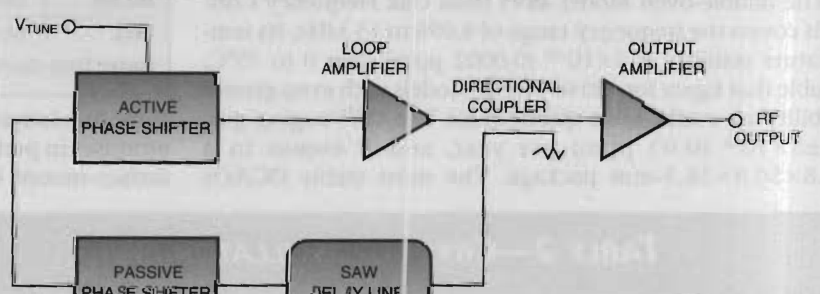


FIGURE A

A SAW delay line is the heart of a series of wide-range VCOs from Andersen Laboratories.

with 100-Hz offset are not on a par with the performance of quartz oscillators but are adequate for many low-cost wireless applications.

Coupled with a PLL, SAW oscillators are capable of sterling performance. A line of SAW-based PLL oscillators from Andersen Laboratories, for example, uses an external 10-MHz reference to provide multiple-frequency outputs at 1500, 1000, 500, 62.5, and 50 MHz. Phase noise with 100-Hz offset is –121 dBc/Hz at 50 MHz and –91 dBc/Hz at 1500 MHz. Andersen also uses SAW elements to make low-phase-noise VCOs (**Figure A**). Vectron, too, makes voltage-controlled SAW oscillators. For example, the 0 to 5V pull range for its 622.08-MHz VCO-600 is ±600 ppm.

Another low-cost method exists for generating frequencies. For lower frequencies, a ceramic resonator offers an alternative to quartz crystals. The PBRC Series from AVX resonates at frequencies as high as 40 MHz and comes in 1.6-mm-thick, low-profile surface-mount packages. Production-quantity prices range from $0.20 to $0.50.

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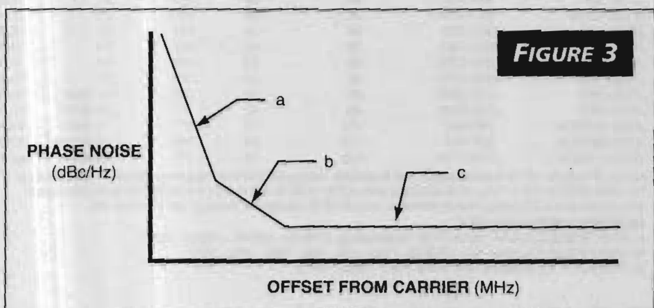
In jitter-intolerant applications, such as GPS, phase noise is an important parameter. Phase noise, the equivalent of digital timing jitter, gives rise to spurious frequency products in mixed analog/digital systems. The data sheets for most OCXOs, which are common in these critical applications, spec phase noise at various offsets, such as 10 Hz, 100 Hz, 1 kHz, and 10 kHz. As an example, Bliley's NV45A with an AT-cut crystal specs 100, 135, 140, and 145 dBc at offsets of 10 Hz, 100 Hz, 1 kHz, and 10 kHz, respectively. The same oscillator with an SC-cut crystal has 5-dBc better phase-noise performance at all offsets.

VCXO, aka frequency modulator

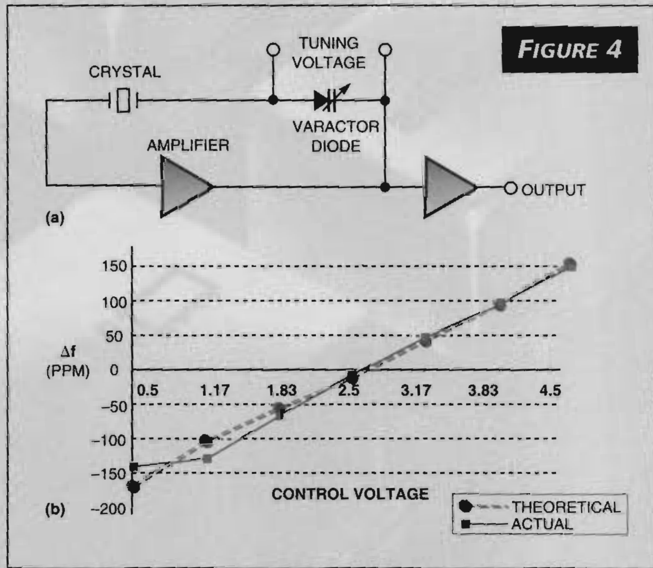
Some oscillators include provisions for fine-tuning the frequency. A voltage-controlled crystal oscillator (VCXO) takes this concept a step further and allows relatively wide frequency control. In a typical VCXO, the tuning voltage varies the capacitance of the varactor diode, thereby pulling the crystal frequency (**Figure 4a**). In a typical pullability curve, the dashed line represents a theoretical, perfectly linear response; the solid line shows the nonlinearities you obtain in a typical, real-world implementation (**Figure 4b**). VCXO data sheets usually spec linearity according to the best-fit straight line drawn through the plot of the measured transfer function.

Most VCXOs use fundamental-mode crystals. The amount of deviation, or pullability, you can obtain is inversely proportional to the square of the overtone number. Thus, a third-overtone crystal allows only one-ninth the tuning range of a fundamental-mode crystal. VCXOs that need higher frequencies than those obtainable from fundamental-mode crystals generally use frequency multipliers. Another method to increase the tuning range, described in **Reference** 5, mixes a VCXO's output with that of a crystal oscillator (**Figure 5**). Here, a 10-MHz signal with ±10-kHz deviation mixed with a 9-MHz signal yields a 1-MHz output with ±10-kHz deviation.

As with virtually all other components, the packaging trend for VCXOs is toward surface-mount devices. A number of recently announced VCXOs reflect this trend; several also join the migration to 3.3V supplies. The surface-mount S1318 from SaRonix covers the 32- to 120-MHz range and offers pullability options of ±25 or ±50 ppm, with ±50-ppm stability under all conditions. The S1318 costs $7 (10,000).



The phase noise in an oscillator consists of flicker noise (a), 1/f noise (b), and the broadband noise floor (c).



As in a TCXO, a varactor diode pulls the crystal's frequency in a VCXO (a). A practical pulling range is approximately ±200 ppm (b).

The J-Type VCXO from Vectron International is also a surface-mount, 3.3V device. It generates frequencies to 155 MHz, with pullability to 150 ppm and 20-ppm temperature stability. The J-Type costs $8.25 (OEM). Champion Technologies' $12 (1000) K1526, a surface-mount VCXO, provides ±120-ppm pullability for devices covering 2 to 40 MHz.

Fordahl's $52.93 (10) DFV S1-KH and -LH surface-mount 3.3 or 5V VCXOs offer ±100-ppm minimum pullability over a 1- to 50-MHz range. Temperature stability is ±15 ppm over 0 to 70°C or ±25 ppm over –40 to +85°C. Options include tristate outputs, restricted pulling, or a ±500-ppm pulling range. The T-VCXO from MF Electronics claims the industry's smallest footprint: 5×7 mm. The device covers 4 to 45 MHz and offers pullability of ±50, ±100, and ±150 ppm. Its stability is 25 ppm maximum over 0 to 70°C; industrial-range (–40 to +85°C) units are also available. The T-VCXO costs $12 (10,000). A final example of recent VCXO offerings is SaRonix's S1550 PECL-compatible VCXO. Packaged in a 14-pin DIP, the $15 (10,000) device covers the 38.88- to 155.52-MHz range and offers stabilities of ±20, ±25, ±50, or ±100 ppm over 0 to 70°C or –40 to +85°C. Pullability options are ±50 or ±100 ppm.

VCOs without an X

In addition to crystal-controlled oscillators, it might be useful to consider voltage-controlled oscillators (VCOs). Thanks to their wide tuning range—far exceeding that of VCXOs—VCOs find widespread use in PLL systems, in which a wide frequency range is important. In these systems, VCOs often work hand in hand with a TCXO or an OCXO, which provides the frequency reference for the PLL. VCOs are also useful for frequency modulation and have a relatively large modulation bandwidth. You can use VCXOs, too, for FM applications, but the modulation bandwidth is

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limited because of the physical and inertial aspects of the crystal. VCOs are usually the oscillators of choice as second local oscillators operating at 100 to 300 MHz and first local oscillators operating at 0.6 to 2.2 GHz in communications systems.

Spec styles for VCOs differ somewhat from those for the crystal oscillators. For example, some data sheets specify carrier-to-noise ratio (CNR) instead of phase noise. It's the same parameter, but the CNR uses a specified bandwidth (for example, 8 kHz) rather than the 1-Hz bandwidth that phase noise uses. For Murata's $7 (10,000) 890- to 915-MHz MQE001-902, for example, the CNR spec is 64 dBc for a 12.5-kHz separation (offset) and an 8-kHz bandwidth. The -902 data sheet also specifies "pushing" and "pulling." Pushing is the frequency deviation resulting from power-supply variations. Pulling (not the same as pullability in a VCXO) is the frequency deviation resulting from a load change that produces a 2-to-1 VSWR change.

A large selection of specialized VCOs is available for spread-spectrum, cellular, GPS, wireless-LAN, and other applications. Z-Communications, for example, offers VCOs for all conceivable applications. An example is the $15 (1000) V580ME03, an 800- to 890-MHz VCO for spread-spectrum applications. The surface-mount device uses a 1 to 8V tuning voltage to obtain a 26-MHz/V tuning sensitivity. Surface-mount VCOs from AVX cover 200 MHz to 2 GHz. The VK, EK, and RK series offer CNRs as high as 117 dBc/Hz at 60-kHz offset. Prices for the AVX VCOs range from $4 to $6 (20,000). Another supplier of a range of VCOs is Mini-Circuits. As an example, the JTOS-3000P surface-mount VCO

MANUFACTURERS OF OSCILLATORS FOR WIRELESS SYSTEMS

For more information on oscillators such as the ones discussed in this article, circle the appropriate numbers on the Information Retrieval Service card or use *EDN*'s Express Request service. When you contact any of the following manufacturers directly, please let them know you read about their products in *EDN*.

Amega Technology
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fax +44 1 256 330302
Circle No. 309

Andersen Laboratories
Bloomfield, CT
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fax 1-203-242-4472
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AVX Corp
Myrtle Beach, SC
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fax 1-803-448-1943
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Bliley Electric Co
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Champion Technologies Inc
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CTS Frequency Controls Corp
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Fordahl USA Inc
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Fox Electronics
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M/A-Com Inc
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Oak Frequency Controls Group
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fax 1-717-486-5920
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fax 1-407-293-2979
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fax 1-425-776-2760
www.pletronics.com
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fax 1-305-594-3973
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SaRonix
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fax 1-415-856-4732
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